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AN AUTOMATIC VACUUM LYSIMETER FOR MONITORING PERCOLATION RATES

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An Automatic Vacuum Lysimeter for Monitoring Percolation Rates[1]

H. R. Duke, E. G. Kruse, and G. L. Hutchinson[2]

A number of techniques have been developed for estimating water flux in field soils.[3, 4,5] However, none of these techniques is designed to measure water flux under conditions of widely fluctuating soil water suction and still yield a sample of percolating water for chemical analysis. During a study of groundwater pollution, the writers developed a device to measure very low percolation rates under conditions of shallow fluctuating water tables and transient soil water suction. The device also provides a percolate sample for laboratory chemical analysis.

The automatic vacuum lysimeter is similar to the pressure plate apparatus used by Cole[4, 5] and others to estimate percolation rates. Automatic regulation of the suction applied to the pressure plate has been provided to minimize convergence effects and maintain representative rates of flow.

Modifications of the equipment and techniques described may be justified when disturbance of the soil is intolerable or where upward movement of water from below the sampling depth is expected. Such modifications are discussed briefly at the end of this paper.

LYSIMETER

The automatic vacuum lysimeters were designed to collect percolate from 40 inches below ground surface. It was assumed that no evaporation would occur from this depth and that any water passing below 40 inches would eventually reach the water table.

The lysimeter (fig. 1) is a soil-filled cylinder having a capillary barrier at the bottom to intercept percolate. A glass bottle, serving as a liquid trap, is suspended beneath this cylinder and connected to the capillary barrier. Vacuum applied to the liquid trap induces suction on the capillary barrier equivalent to the natural water suction at the same depth in undisturbed soil outside the cylinder.

LYSIMETER CYLINDER

The lysimeter cylinder (fig. 2) is constructed from a 36-inch section of 12-inch (nominal) well casing with a wall thickness of 1/4 inch. A circular steel flange rolled from a 1-1/4- x 1-1/4- x 1/4-inch angle is welded 2 inches below the top edge of the cylinder. This flange is drilled to accept four 3/8- x 2-inch bolts which are used as leveling devices. Additional holes are provided for securing a temporary steel cover when filling the lysimeter and for attaching eyebolts used to lift the cylinder.

A 1/4- x 1/4-inch groove is machined inside the cylinder approximately 1 inch from the bottom end. This groove serves as a seat for securing the bottom plate with four setscrews. The bottom is made from 3/16-inch steel place, about 1/4 inch smaller in diameter than the cylinder inside diameter. This plate is welded to an angle iron ring, with the horizontal flange toward the inside, so that it will slip freely into the lysimeter cylinder. Four 3/8-inch nuts welded over peripheral holes in the lower flange hold the setscrews that secure the bottom plate in the lysimeter groove.

To facilitate removal of the lysimeter for maintenance, the lysimeter cylinder is installed in a larger outer

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[1] Contribution from the Northern Plains Branch, Soil and Water Conservation Research Division, Agricultural Research Service, U.S. Department of Agriculture, in cooperation with the Colorado Agricultural Experiment Station, Fort Collins.

[2] Agricultural Engineer, Agricultural Engineer, and Soil Scientist, respectively, ARS, USDA, Fort Collins, Colo.

[3] Byrne, G. F. Drummond, J. E., and Rose, D. W. A sensor for water flux in soil. "Point Source" instrument. Water Resources Res. 3 (4): 1073-78. 967.

[4] Cole, D. W. Alundum Tension Lysimeter. Soil Sci. 85 (6): 293-296. 1958.

[5] Cole, D. W. A system for measuring conductivity, acidity, and rate of water flow in a forest soil. Water Resources Res. 4 (5): 1127-36. 1968.

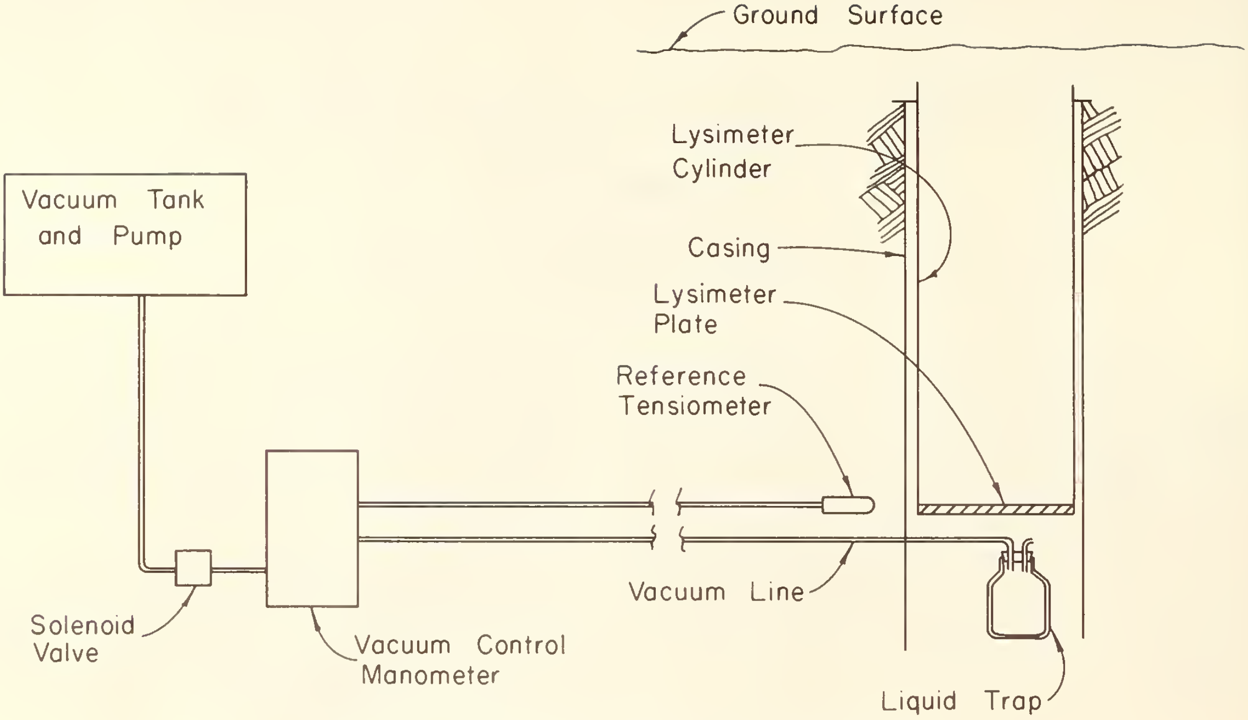

Figure 1.—Schematic diagram of an automatic vacuum lysimeter.

casing. This casing is a 48-inch section of 14-inch nominal diameter well casing with a wall thickness of about 3/16-inch. A 1-inch wide ring of 3/16-inch steel plate is welded around the casing at the top. This ring provides a support surface for the leveling bolts of the lysimeter cylinder.

LYSIMETER PLATES

Several commercially available materials were tested in the laboratory to determine their suitability for use as capillary barriers. Final selection was based on four primary criteria: (1) A bubbling pressure approaching one bar was necessary to utilize the maximum range of tension available from a vacuum system; (2) an inert material was needed, since percolate samples were to be subjected to chemical analyses; (3) sturdy construction; and (4) reasonable cost. Neoprene-backed ceramic plates used in pressure plate extraction apparatus were selected. The plates are 11½ inch in diameter and about 1/4 inch thick, with an external pressure tap in the ceramic face near one edge.

Since the pH of test samples of nearly neutral soil solution was increased to almost 11.5 during passage through the ceramic plates, chemical pretreatment of the plates to remove excess soluble bases was necessary. Each plate was leached with about 30 liters of 0.1 N HCl, following by about 5 liters of demineralized water. The pH of the leachate stabilized at about pH 1.1, after 15 to 25 liters had passed through the plates, and then quickly approached neutrality when the leaching solution was changed from 0.1 N HCl to demineralized water. After washing was completed, the exchange capacity of the plates was saturated with calcium by leaching with about 5 liters of 0.02 m $CaCl_2$. Finally, the plates were again flushed with about 5 liters of demineralized water to remove excess $CaCl_2$.

After pretreatment with dilute acid and demineralized water, but before saturation with $CaCl_2$, one of the ceramic plates was tested to determine its interaction with a solution of known composition. The plate, initially saturated with demineralized water, was leached with an aqueous solution of KH phthalate, and $(NH_4)_2HPO_4$, K, NH_4-N, PO_4-P, and pH were determined for increments of the leachate. The first sample of leachate was discarded because it contained the water in the plate at the beginning of the test. Results of the test are given in the following table.

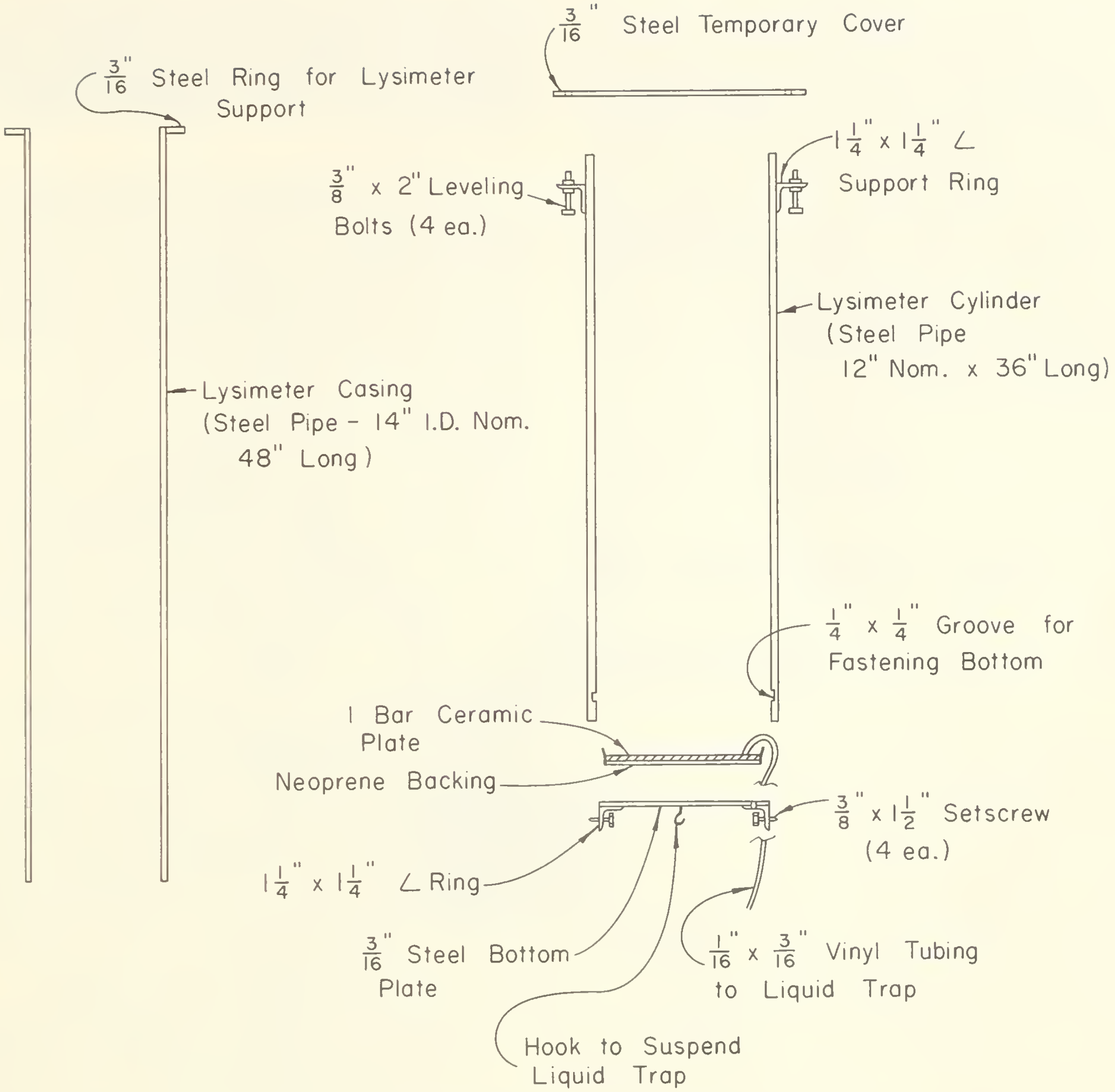
3/16" Steel Temporary Cover
3/16" Steel Ring for Lysimeter Support
1 1/4" x 1 1/4" ∠ Support Ring
3/8" x 2" Leveling Bolts (4 ea.)
Lysimeter Cylinder (Steel Pipe 12" Nom. x 36" Long)
Lysimeter Casing (Steel Pipe - 14" I.D. Nom. 48" Long)
1/4" x 1/4" Groove for Fastening Bottom
1 Bar Ceramic Plate
Neoprene Backing
3/8" x 1 1/2" Setscrew (4 ea.)
1 1/4" x 1 1/4" ∠ Ring
3/16" Steel Bottom Plate
1/16" x 3/16" Vinyl Tubing to Liquid Trap
Hook to Suspend Liquid Trap

Figure 2.—Detail drawings of a lysimeter.

Sample	*Volume* *Ml.*	*pH*	*K* *Mg./l.*	*NH_4-N* *Mg./l.*	*PO_4-P* *Mg./l.*
Leaching solution	--	4.1	170	1.1	1.1
Leachate sample 1	250	([1])	([1])	([1])	([1])
Leachate sample 2	300	4.0	41	1.0	0.7
Leachate sample 3	350	4.1	140	1.1	.9
Leachate sample 4	330	4.1	160	1.1	1.0

[1] Discarded.

Assuming that the plate was essentially saturated with K at the completion of the test, its cation exchange capacity is computed to be less than 2 milliequivalents, which is not high enough to cause serious alterations in the chemical compositon of extracted soil solution, except when an extremely small volume of percolate or an extremely dilute sample of percolate is obtained. Ammonium concentration and pH of the leaching solution were little changed during transport through the ceramic plate and even phosphate was not strongly absorbed. Probably, a greater percentage of the phosphate would be absorbed from a solution of higher pH.

LIQUID TRAP

Percolating water is collected and stored in a 1,000-ml. glass bottle, suspended beneath the lysimeter (fig. 3). The bottle is fitted with a three-hole neoprene stopper. Three lengths of 1/8-inch outside diameter (O.D.) brass tubing provide for attachment of the necessary vinyl tubing. The intake tube, connected with the capillary barrier through a 1/4-inch diameter access hole drilled near the edge of the lysimeter bottom plate, extends about 1 inch beneath the stopper. The vacuum supply tube extends a shorter distance into the bottle to prevent water droplets being drawn from the intake tube into the vacuum line. A third tube, which extends to the bottom of the bottle, is used for withdrawing the percolate sample. A vinyl line connected to the withdrawal tube extends to the ground surface adjacent to the lysimeter.

During normal operation, the withdrawal line is clamped closed, and the pressure in the vacuum line is regulated to ambient soil water suction through the automatic control system. This pressure is transferred to the capillary barrier, thus inducing a hydraulic gradient within the lysimeter equivalent to that in the surrounding soil.

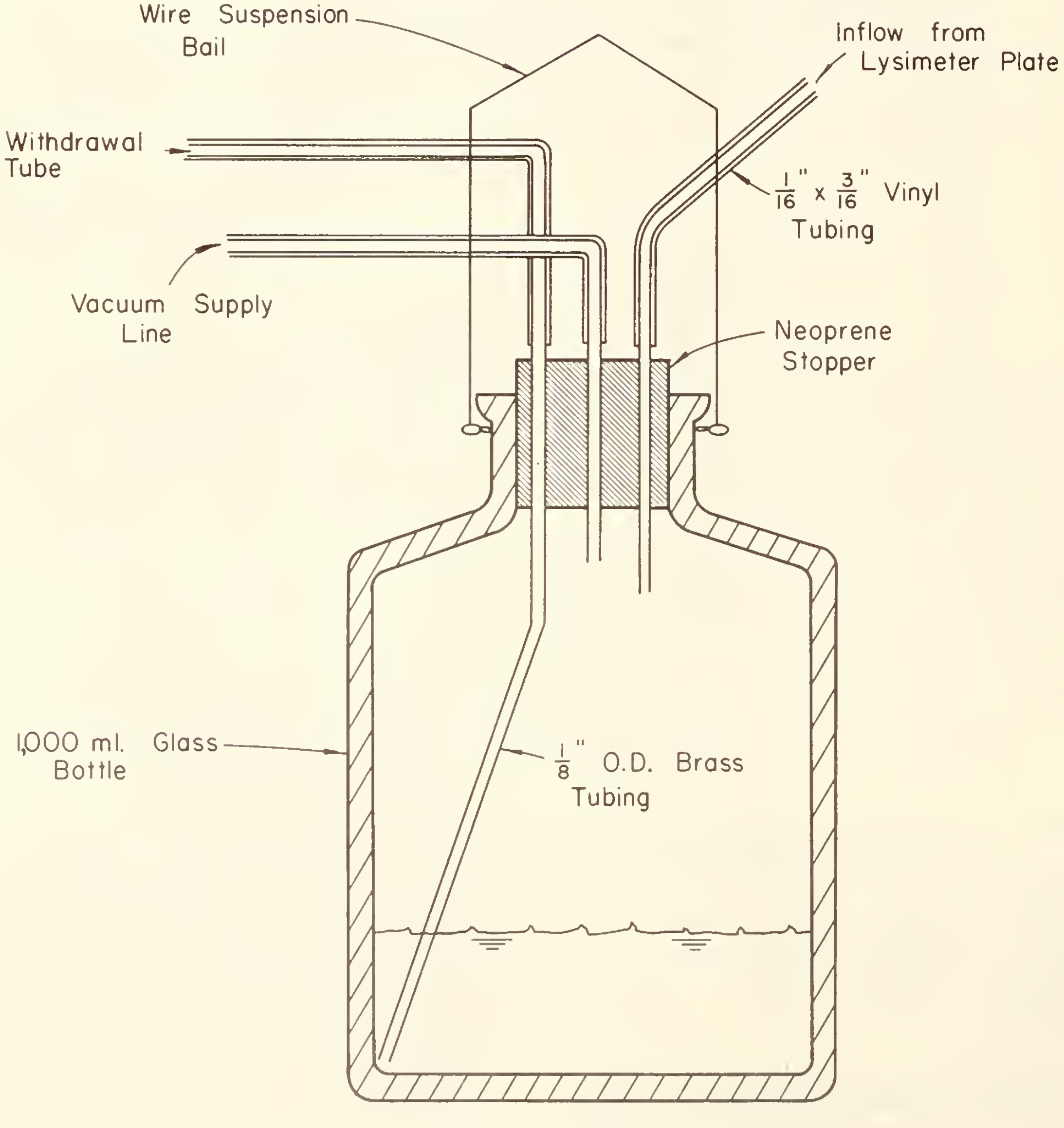

Figure 3. Detail of percolate collection bottle.

To withdraw the percolate sample, a second liquid trap is connected to the withdrawal line and to the vacuum supply system via a temporary surface line. The lysimeter vacuum line is then vented to the atmosphere via a three-way valve at the control station. Thus, liquid is forced out of the lower trap, through the withdrawal line, and collected at the surface for volumetric and chemical analyses.

AUTOMATIC CONTROL SYSTEM

TENSIOMETER

The heart of the automatic vacuum control system is the reference tensiometer (fig. 4). The tensiometer, when installed in undisturbed soil at the same level as the lysimeter plate, serves as a sensor to detect ambient soil water suction. Reference tensiometers are installed immediately adjacent to each lysimeter (as far as 100 feet from the control station). To facilitate removal of air from the long connecting lines, the tensiometers are designed to permit periodic flushing without removing the tensiometer.

The tensiometer material is 1 bar ceramic tubing about 3/8 in in O.D., 3/16 inch in inside diameter (I.D.), and 2 inches long. An acrylic plug cemented into one end protects the ceramic during installation and seals the end of the tensiometer. The other end of the ceramic tube is fitted with a modified brass Polyflo[6] (1/4 inch O.D x 1/8 inch I.D. polyethylene tubing) connector. A 2-inch length of 1/16-inch O.D. brass tubing is soldered inside the Polyflo connector. This polyethylene tubing serves as the tensiometer lead line.

A second brass connector is modified to allow external feeding of the tensiometer bleed line. A 1/8-inch hole is drilled through one of the wrench flats of the connector into the bore, and a length of 1/16-inch brass tubing bent in an L-shape is fitted through the hole and out one end of the connector. This tube is soldered in place, being careful not to plug the bore of the connector. The two concentric tubes are fastened to this connector, with the other end of the connector fastened to the underground tensiometer line leading to the control station. A length of 3/16 inch O.D. x 1/16 inch I.D. vinyl tubing is connected to the external end of the bleed tube and securely clamped.

MANOMETER

Lysimeter suction is regulated through a three-tube mercury manometer (fig. 5). The manometer, constructed of acrylic plastic, serves as a single pole, double-throw electrical switch. The left tube is connected through a port at the bottom to the tensiometer line and is approximately half filled with water. This leg is connected across the top to the center tube, which in turn is connected across the bottom with the right tube. The center and right-hand tube are each half filled with mercury. The connected space between water and mercury in the left and center tubes is filled with light motor oil which acts as an electrical insulator.

Three stainless steel electrodes are installed in the mercury columns to provide control for a solenoid valve. The common electrode is installed into the connecting space between the center and right tubes and is cemented in place. The remaining two electrodes, which are 30 cm. long, pass into the two tubes from the top. An "O"-ring seal at the top allows for adjustment of electrode spacing. The electrodes are preset to compensate for the height of water column in the tensiometer line. Allowance is made for a brief excursion of the mercury column between breaking contact with one electrode and making contact with the other. This excursion determines the variation from ambient soil water suction allowed in the vacuum line. The variation can be held to 2 mm. Hg or less. The upper end of the right tube is connected with a tee to both a two-way solenoid valve and the vacuum line leading to the lysimeter. A three-way manual valve is connected in the line leading from the solenoid valve to the manometer to provide for recovering the percolate sample. During normal operation, this valve connects the solenoid valve with the manometer and vacuum line. For sample recovery, the valve is turned to close the line from the solenoid valve and vent the lysimeter vacuum line to atmospheric pressure.

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[6] Trade names are used in this publication solely for the purpose of providing specific information. Mention of a trade name does not constitute a guarantee or warranty of the product by the U.S. Department of Agriculture or an endorsement by the Department over other products not mentioned.

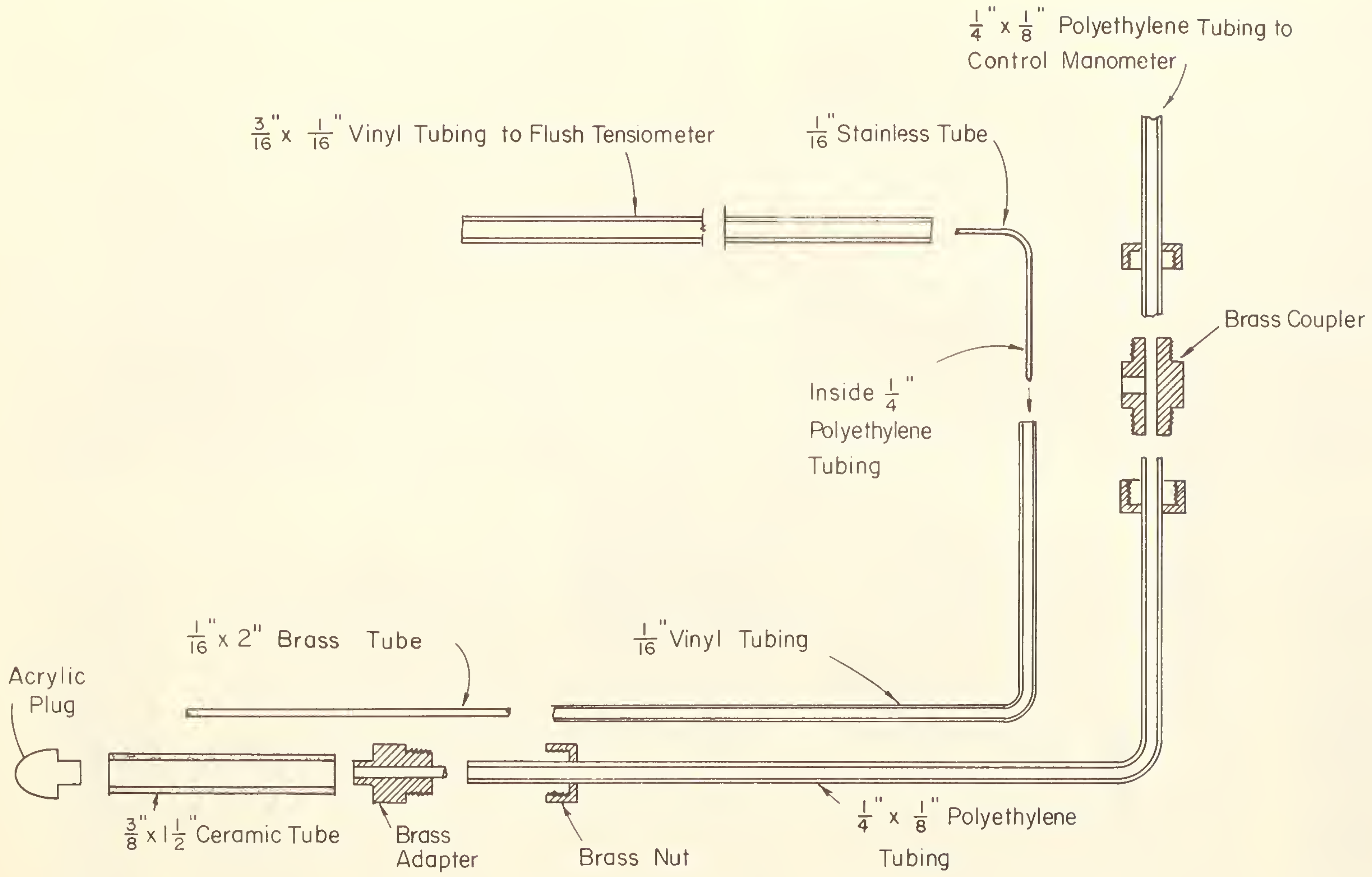
$\frac{1}{4}$" x $\frac{1}{8}$" Polyethylene Tubing to Control Manometer
$\frac{3}{16}$" x $\frac{1}{16}$" Vinyl Tubing to Flush Tensiometer
$\frac{1}{16}$" Stainless Tube
Brass Coupler
Inside $\frac{1}{4}$" Polyethylene Tubing
Acrylic Plug
$\frac{1}{16}$" x 2" Brass Tube
$\frac{1}{16}$" Vinyl Tubing
$\frac{3}{8}$" x $1\frac{1}{2}$" Ceramic Tube
Brass Adapter
Brass Nut
$\frac{1}{4}$" x $\frac{1}{8}$" Polyethylene Tubing

Figure 4. Exploded diagram of reference tensiometer.

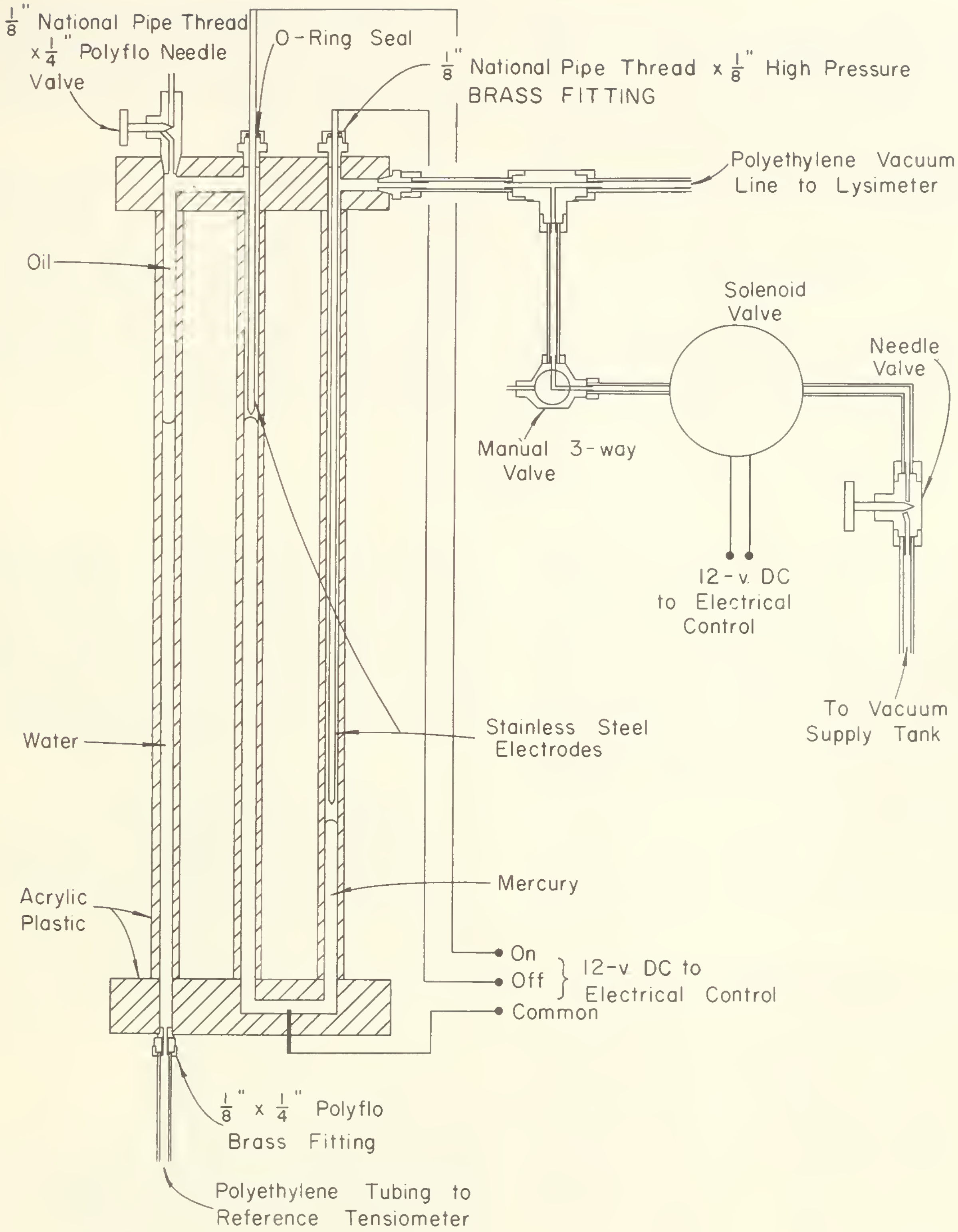
$\frac{1}{8}$" National Pipe Thread x $\frac{1}{4}$" Polyflo Needle Valve
O-Ring Seal
$\frac{1}{8}$" National Pipe Thread x $\frac{1}{8}$" High Pressure BRASS FITTING
Polyethylene Vacuum Line to Lysimeter
Oil
Solenoid Valve
Needle Valve
Manual 3-way Valve
12-v. DC to Electrical Control
To Vacuum Supply Tank
Water
Stainless Steel Electrodes
Mercury
Acrylic Plastic
On
Off
12-v. DC to Electrical Control
Common
$\frac{1}{8}$" x $\frac{1}{4}$" Polyflo Brass Fitting
Polyethylene Tubing to Reference Tensiometer

Figure 5. Vacuum control manometer.

The solenoid valve has a 12-v. DC coil and 5/64-inch port. Because this port allowed air to flow through the valve too rapidly, causing the manometer to "overshoot," a needle valve was installed between the solenoid valve and the vacuum supply tank. The needle valve allows adjustment of air flow to provide relatively slow pressure changes in the vacuum line and aids in precise pressure control.

OPERATING PRINCIPLES

As soil water suction increases, water is drawn through the tensiometer into the surrounding soil. This draws the mercury up the center tube of the manometer until it contacts the center electrode. The circuit thus complete provides the signal to open the solenoid valve. As air is bled from the vacuum line, the mercury column rises in the right-hand tube until it contacts the right electrode. Completion of this circuit closes the solenoid valve, and the cycle is completed.

Note that a small air bleed in the vacuum lines will cause the same response of the manometer system as will an increase in soil water suction. Without a minor bleed, the only means of increasing pressure in the vacuum line to the lysimeter is by percolate displacing air in the liquid trap. Since such a response is extremely slow, it is advisable to provide an air bleed into the vacuum line if a decrease in soil moisture tension may occur. Present installations have sufficient air bleed so that the solenoid valve operates every 5 to 10 minutes.

VACUUM SUPPLY

An automatically controlled vacuum pump provides a continuous vacuum supply for lysimeter operation. Figure 6 shows the vacuum control system. A vane-type rotary pump directly coupled to a 1/4 hp. electric motor is used. The pump has a capacity of 4.1 cubic feet per minute at 27 inches of Hg and has proved more than adequate to serve three lysimeters. A 12-gallon air compressor tank is mounted directly beneath the pump to provide storage capacity. The pump is equipped with a check valve to eliminate leakage through the pump when not operating.

The vacuum pump is controlled by a mercury manometer which monitors the vacuum tank pressure. This two-tube, acrylic manometer has one leg connected into the vacuum line and the other vented to atmosphere. Three pairs of on-off contacts are cemented into the manometer tube at differential levels representing 0.3, 0.5, and 0.9 local atmosphere. This variable supply pressure requires minimum demand on the pump and maintains the vacuum supply pressure within a narrow range to ensure predictable operation of the system.

ELECTRICAL CONTROL SYSTEM

Figure 7 is a schematic diagram of the electrical control circuit. All manometer electrodes and the

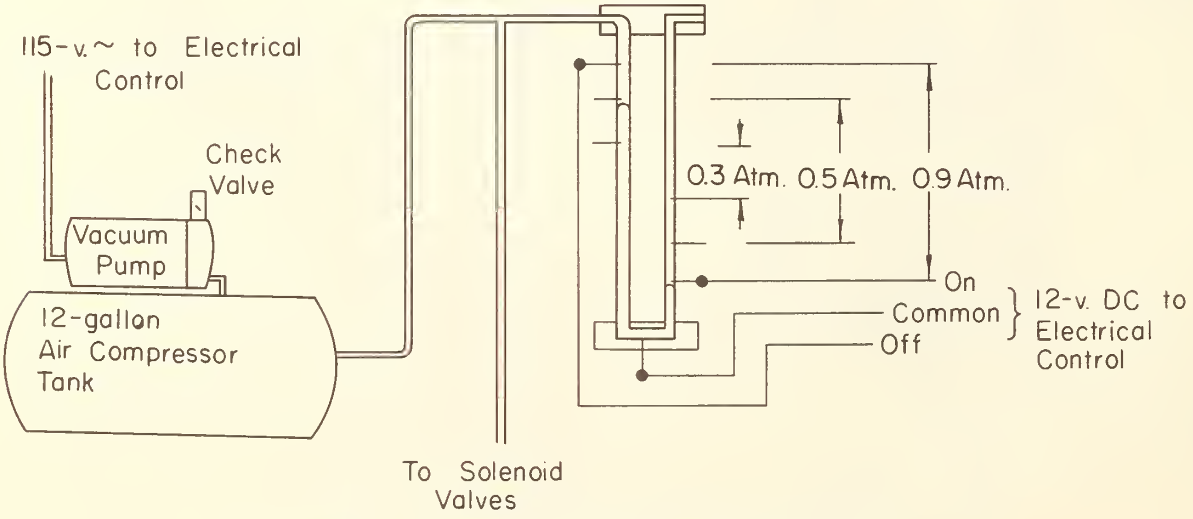
115-v. ~ to Electrical Control
Check Valve
Vacuum Pump
12-gallon Air Compressor Tank
0.3 Atm.
0.5 Atm.
0.9 Atm.
On
Common
Off
12-v. DC to Electrical Control
To Solenoid Valves

Figure 6. Schematic diagram of vacuum supply system.

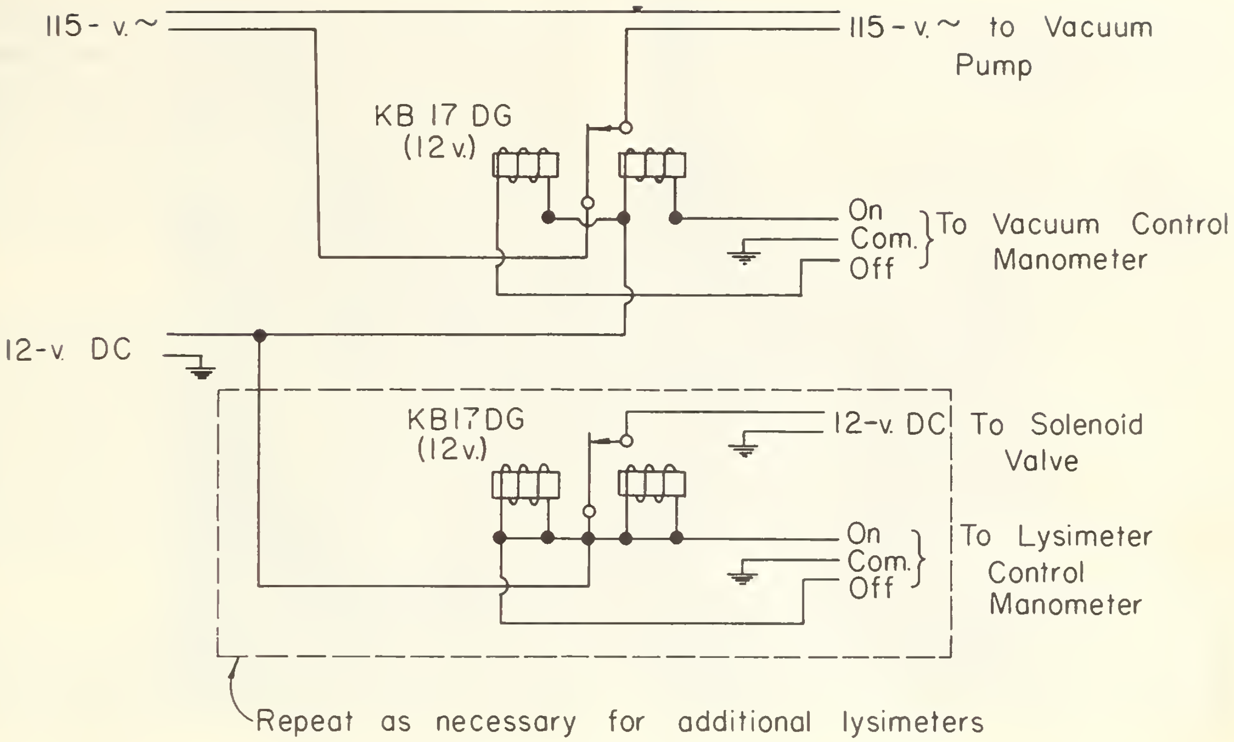

Figure 7. Schematic diagram of electrical control circuit.

solenoid valves are operated by a 12-v. DC power source to minimixe the danger of electrical shock. The power supply used for this system is an inexpensive 12-volt automotive battery charger.

Both solenoid valve and vacuum pump switching are accomplished by using two-coil 12-v. DC mechanical latching relays. Completion of a manometer circuit energizes one coil of the relay to close the contact points. The points remain closed, even after the coil circuit is broken, until the second manometer circuit is completed. Energizing the second relay coil unlatches the relay, allowing the points to drop open. Presently, four such latching relays are in use—one to control the vacuum pump and one to control each of three solenoid valves.

INSTALLATION

Three vacuum lysimeters have been installed in each of two sites. These installations are a part of a study of groundwater pollution from cattle feedlot operations. The samples collected will be analyzed for both percolation rates and chemical constituents, the ultimate objective being to estimate the total pollutant load contributed by the feeding operations.

The first field site is nearly level (< 0.5 percent slope) with approximately 12 inches of sandy soil overlying an aquifer material ranging in particle size from coarse sand to cobbles. The second site lies on a deep sandy loam with a uniform slope of about 6 percent. Neither of these soils exhibits any significant structural elements within the feedlot area. The lysimeters are located in three separate regions of each lot: (1) Immediately behind the feeding apron where excreted moisture is greatest, (2) approximately 30 feet from feed bunks in major traffic area with moderate excretion, and (3) near center of pen where traffic and excretion are minor.

Before installation of the lysimeter, the control lines (one line for tensiometer; another for the vacuum) were buried from the control building to each lysimeter location. The manure pack layer (approximately 24 inches in diameter) was removed intact from above each lysimeter location and set aside for later replacement. An 18-inch diameter hole was dug to a depth of 6 inches (the installed depth of top of lysimeter cylinder below the surface) and material removed was saved for later replacement.

A temporary cover fastened atop the lysimeter cylinder allowed the lysimeter to be inverted for filling. As each 2-inch layer of soil was removed from the hole a sufficient amount was placed in the lysimeter to fill it to the same depth. This material was tamped to simulate the original density of the soil. After filling the lysimeter, the hole was dug to a depth of 60 inches to allow setting the outer casing.

When the hole was completed, a presaturated tensiometer was connected to the tensiometer lead line. The tensiometer was forced into the side of the hole 40 inches below the surface and soil tamped firmly around it to obtain good contact. The tensiometer bleed line was passed to the surface for later positioning. The outer cylinder was then lowered into place in the hole, with the upper flange 8 inches below land surface. The cylinder was plumbed and backfill tamped around it.

Before placing the ceramic plate in the lysimeter cylinder, the vacuum line was attached to the plate through the liquid trap. Approximately 72 inches of 1/16- x 3/16-inch vinyl tubing was connected to the sample recovery tube of the trap and clamped shut. The vacuum system was then placed under about 10 cm. Hg tension to prevent dewatering the capillary barrier. The soil at the bottom of the cylinder (cylinder inverted) was prepared for placement of the plate by leveling it and leaving slightly more than enough space for the plate and cylinder bottom. Sufficient fine-textured soil was added so that the plate was held firmly against the soil column with the cylinder bottom in place. To insure initial contact between plate and soil, 200 ml. of water was distributed over the soil surface. Finally the ceramic lysimeter plate was firmly seated (fig. 8) and the cylinder bottom was bolted in place.

The lysimeter was set upright, suspended over the exposed casing and the liquid trap fastened beneath the cylinder (fig. 9). The lysimeter and liquid trap were then lowered into the casing, being careful not to pinch the vacuum and sample recovery lines. Installation was completed by adjusting the leveling bolts on the lysimeter flange to plumb the lysimeter, by removing the temporary cover plate, and by replacing the upper layer of soil and manure pack.

The tensiometer line was filled by placing the bleed line, exposed at the lysimeter, in a container of deaerated water, connecting the end inside the control

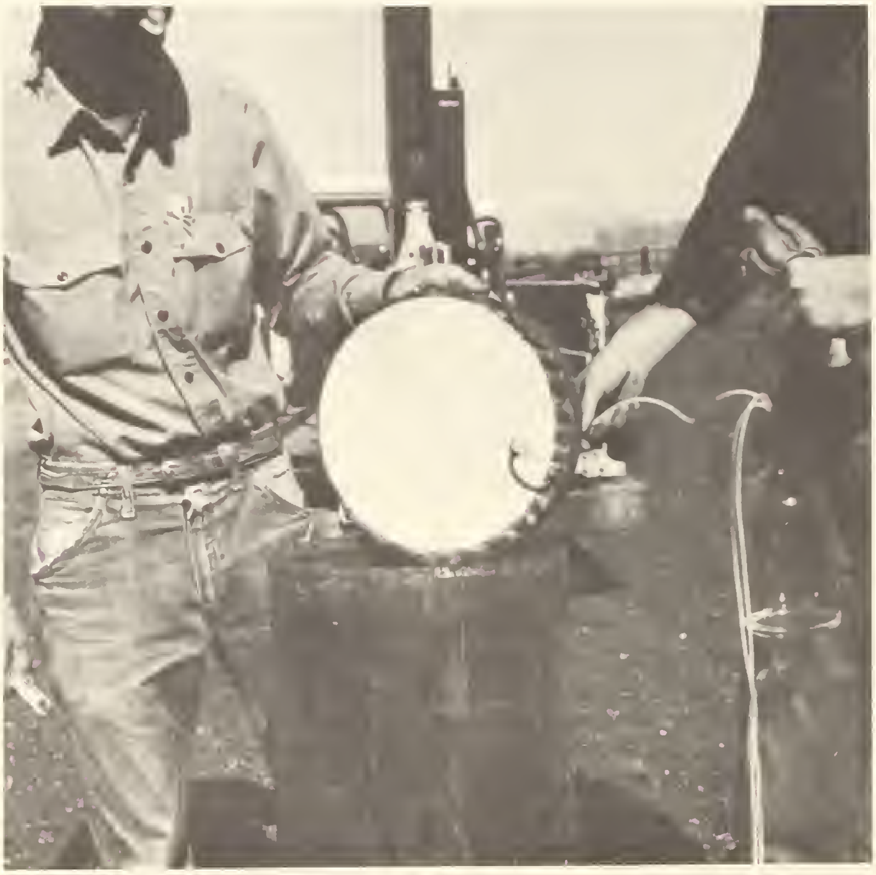

Figure 8.—Installing lysimeter plate in sample cylinder.

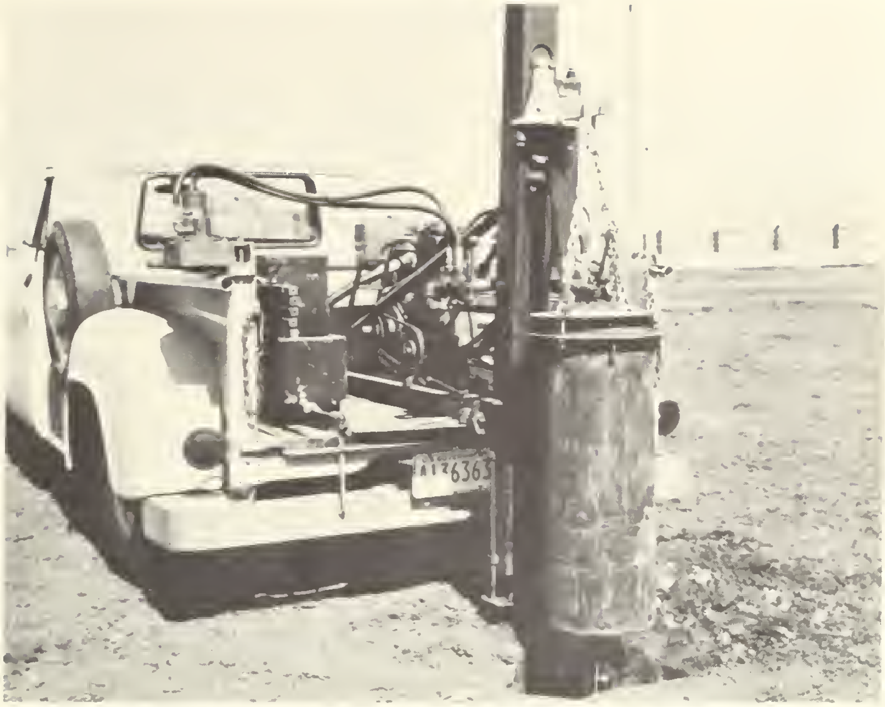

Figure 9.—Lysimeter and percolate collection bottle ready to be set in place.

building through a liquid trap to the vacuum supply, and drawing water through the line. After all air had been removed, the tensiometer line was connected to the control manometer. The manometer was then filled with oil and all air evacuated.

The two lines (sample recovery and tensiometer bleed lines) emerging at the lysimeter site were tightly clamped, marked, and covered with a polyethylene bag. The bag was buried about 6 inches deep adjacent to the lysimeter for later recovery when needed (fig. 10).

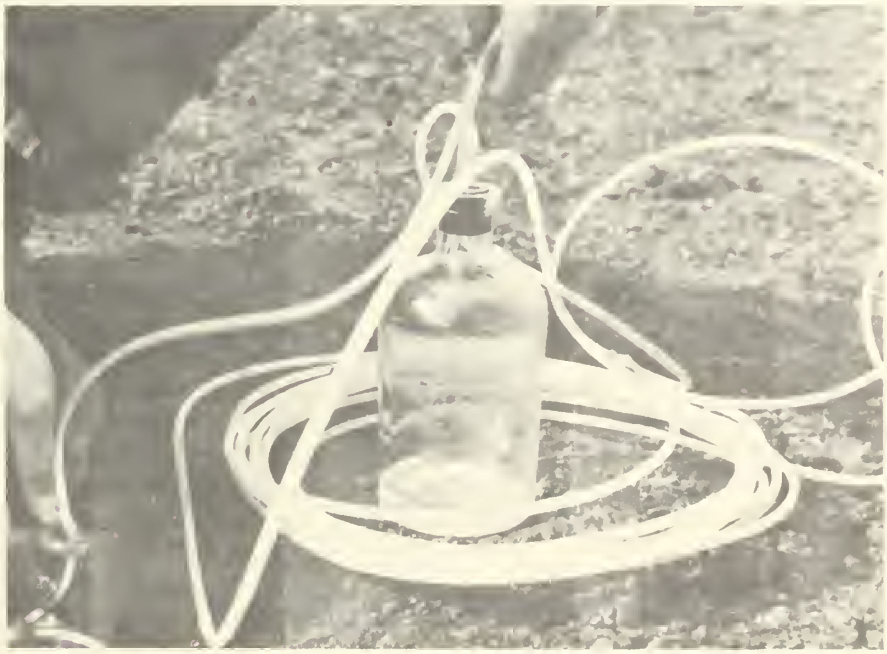

Figure 10.—Recovery of percolate sample.

RESULTS

The lysimeters at the level feedlot site have been in operation about 10 months. A vacuum gage attached to the vacuum side of one manometer has indicated a range of suction between 100 and 300 mb. during this time.

Percolate samples are being recovered at 4-week intervals, since percolation rates are quite low. More frequent recovery does not yield sufficient volume of percolate for the desired chemical analyses. Average percolation rates over this period have ranged from 3.0 x 10^{-3} in./day in the drier areas. Although a water balance has not been computed to check the validity of these percolation rates, they are of the same order of magnitude as those estimated from conductivity tests using ambient suction and an assumed unit hydraulic gradient.

SUGGESTIONS FOR MODIFICATIONS

As previously mentioned, the soils encountered in this study are quite sandy and exhibit little or no structure. For these reasons, the writers chose to enclose the soil sample in a cylinder to facilitate maintenance. The consequences of sample disturbance were considered minimal so long as the natural density was duplicated in the cylinder. In soils having significant structural elements or where development of plant roots will be influenced by the sample cylinder, the automatic control features of this system may be used with an open plate buried in undisturbed soil.

Experimental results of Anat, Duke, and Corey[7] showed that upward flow from the 40-inch depth in these soils would be very small, especially with a manure pack to insulate the surface. For installation at shallow depths where significant upward flow will occur, it may be desirable to modify the liquid trap. By extending the inflow tube to the bottom of the liquid trap and modifying the sampling procedure, the lysimeter can supply any evaporative demand and measure percolation rates.

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[7] Anat, A., Duke, H. R., and Corey, A. T. Steady upward flow from water tables. Colo. State Univ. (Fort Collins) Hydrology Paper No. 7. 1965.

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